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Laser Hazard Analysis for Airborne AURA (Big Sky Variant) Proteus Platform

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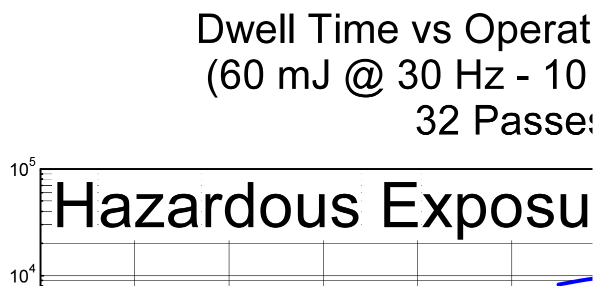
Abstract

A laser safety and hazard analysis was performed for the airborne AURA (Big Sky Laser Technology) lidar system based on the 2000 version of the American National Standard Institute's (ANSI) Standard Z136.1, *for the Safe Use of Lasers* and the 2000 version of the *ANSI Standard Z136.6, for the Safe Use of Lasers Outdoors*. The AURA lidar system is installed in the instrument pod of a Proteus airframe and is used to perform *laser interaction* experiments and tests at various national test sites. The targets are located at various distances or ranges from the airborne platform. In order to protect personnel, who may be in the target area and may be subjected to exposures, it was necessary to determine the Maximum Permissible Exposure (MPE) for each laser wavelength, calculate the Nominal Ocular Hazard Distance (NOHD), and determine the maximum "eye-safe" dwell times for various operational altitudes and conditions. It was also necessary to calculate the appropriate minimum Optical Density (OD_{min}) of the laser safety eyewear used by authorized personnel who may receive hazardous exposures during ground base operations of the airborne AURA laser system (system alignment and calibration).

Summary

Under "worst case" exposure conditions for the airborne AURA laser, operating at maximum output and the Proteus operating at expected altitudes at normal air speed for the maximum dwell time on target for an 8-hour flight, the laser hazard presented to personnel on the ground in the target area is **Class 1** and is both eye and skin safe.



Changes In Laser Hazard Conditions

The laser hazard analysis presented here is valid for the current laser parameters and expected flight conditions of the Proteus platform. Significant changes in the laser, telescope system or the airborne platform will necessitate a laser safety review and new laser hazard analysis.

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I. Introduction

A. Overview

The AURA Airborne Remote Sensing System is centered on a Big Sky Laser Technology, Class 4, frequency tripled Q-switched Nd:YAG laser system, which can produce radiant outputs in the ultraviolet (UV) at 355 nanometers and in the infrared (IR) at 1064 nm. The laser is mated to a gimbaled telescope, which is used to direct the laser output to "target" points on the ground or targets between the aircraft and the ground (cloud sampling) and retrieve or capture "target return spectra" for analysis. The remote sensing system is mated to a Proteus airborne platform.

B. Modes of Operation

There are two principle modes of system operation to consider when performing a laser hazard analysis: airborne and ground operation.

1. Airborne Operation

The Airborne AURA Remote Sensing System laser is primarily operated while the Proteus is airborne over an area of concern (target area). While the system is airborne, the cruising altitude is maintained so as to present a Class 1 laser hazard to personnel in the "target' area. Typical operation is at altitudes of 1 to 5 kilometers above ground level (AGL). The gimbaled lidar system is designed to look forward by as much as 27 degrees (off of vertical) and be able to hold a point, locked on a target (until 27 degrees aft). During normal testing the Proteus can make up to four passes (over the target) per hour. Airborne operation is not expected to exceed 8 flight hours in a 24-hour period.

The laser may be operated (pointed 27 degrees forward) while the Proteus is flying at a minimum altitude of one kilometer above ground level (AGL), to and from the target area or prior to target "lock-on".

2. Ground Operation

The Airborne AURA laser may also be operated while it is on the ground. Ground operations are primarily for the purpose of performing optical alignments and system calibrations. Some limited laser-interaction tests may be performed during ground operation.

II. Big Sky Laser Parameters

Class 4 Laser:

Primary wavelength:	355 nm
Primary Radiant Output (typical):	50 mJ
Primary Radiant Output (maximum):	60 mJ
Secondary wavelength:	1064 nm
Secondary Radiant Output (typical):	0.5 mJ - 1.5 mJ
Secondary Radiant Output (maximum):	2 mJ
Pulse Width:	10 nanoseconds
Pulse Repetition Frequency:	30 Hz

System Telescope:

Beam Divergence:	500 x 10^{-6} radians
Exit Beam Diameter:	1.0 cm

Airborne Test Parameters

Operational Altitude Range	1 to 5 km
Point Angles	27˚ Forward to 27˚ Aft 12˚ Starboard to 12˚ Port
Typical Air Speed	90 Knots
Time on target (maximum)*	110 second
Target passes per hour (typical)	4
Flight time per 24-hours (typical)	8 hours (maximum)

**Dependent on Altitude and "Ground Speed"*

III. Maximum Permissible Exposure

A. UV Region (180 nm < λ < 400 nm)

The UV wavelength region from 180 nm to 400 nm is a "dual limit" region. The dual limits are comprised of the "**photochemical limit**" (the *left-hand* formula in *Table 5a* of the ANSI standard) and the "**thermal limit**" (the *right-hand* formula (notes) of *Table 5a* of the ANSI standard). The appropriate MPE is determined from the smallest value of these two limits [*ANSI Std. Z136.1-2000 (Table 5a)(notes)*].

1. Appropriate MPE Determination

The appropriate MPE for repetitively pulsed lasers is always the **smallest** of the MPE values derived from ANSI Rules 1 through 3 [*ANSI Std. Z136.1-2000 (8.2.3)*]. Rule 1 pertains to a single pulse exposure. ANSI Rule 2 pertains to the average power for thermal or photochemical hazards per pulse and Rule-3 pertains to the multiple-pulse, thermal hazard [*ANSI Std. Z136.1-2000 (8.2.3)*].

Region (315 nm < λ < 400 nm)

The appropriate MPE formula present in *Table 5a* of the *ANSI Std. Z136.1-2000* for laser emission wavelengths from 315 nm to 400 nm is the same "form" for both the photochemical and thermal limits. The MPE for UV laser emission wavelengths longer than 280 nm is de-rated by a factor of 2.5 if exposures to these wavelengths are expected on successive days [*ANSI Std. Z136.1-2000 (8.2.3.1)*]. The photochemical limit is equal to the thermal limit in this wavelength region for exposure times of 1 nanosecond to 10 seconds, but for exposures of 10 to 30,000 seconds the photochemical limit MPE is defined as: 1 J/cm^2 [*ANSI Std. Z136.1-2000 (Table 5a)*].

2. Appropriate Exposure

The MPE (derived for each to the three rules) is dependent on the expected exposure duration. The actual exposure for the airborne operation is variable dependent on the particular laser-interaction test involved. The maximum dwell time per pass over the target area is limited to ± 27-degree sweep (forward to aft) and is also dependent upon the forward air speed and the operational altitude. The altitude of the Proteus for the expected exposure will be maintained such as to present a Class 1 laser hazard to personnel in the "target" area.

Personnel in the target area may fall into one of two categories: authorized and unauthorized.

Authorized personnel are necessary to the “test” and are expected in the area and are expected to have successive day exposures and are required to wear appropriate personal protective equipment (PPE) such as: eye protection, long sleeve clothing and use sunscreen to protect exposed skin. Authorized personnel have been granted permission to be inside the control area.

Unauthorized personnel are not expected in the target area and will be assumed not to have appropriate PPE. Unauthorized personnel have not been granted permission to be in the control area and have in fact violated the boundary of the control area (target and buffer areas).

The suggested exposure for authorized personnel inside the NHZ of the Airborne BSLT AURA laser system during ground operations is **30,000 seconds** [*ANSI Std. Z136.1-2000 (Table 4a)*] with successive day exposures.

The assumed exposure for **unauthorized personnel** that enter the target area is set at the **maximum exposure for a single pass over the target** area.

The ANSI Standard Z136.1-2000 suggested exposure (maximum) duration is used to calculate the appropriate MPE used for laser safety eyewear determination specific to the ground operation of the laser system.

The actual expected exposure (accumulated in a 24-hour period) is used to determine the Nominal Ocular Hazard Distances (NOHD) as a function of operational altitudes for airborne operation.

Actual exposure is used because the excessive exposure (30,000 seconds) would adversely affect the mission by requiring the Proteus to fly at much greater altitudes than really necessary to produce a “Class 1” exposure at ground level. An exposure of 30,000 seconds is excessive because the laser will not be active for that length of time and it is unreasonable that an unauthorized individual would remain “intrabeam” undetected in the target area for that length of time.

Rule 1 (Single Pulse):

The appropriate MPE is derived from the smallest of the photochemical and thermal limits. For an exposure between 1 nanosecond and 10 seconds the photochemical limit is equal to the thermal limit. The pulse width of the BSLT laser is 10 nanoseconds.

$MPE_{s.p.}$ = min [photochemical limit, thermal limit] {Dual limit region}

= min [($0.56t^{0.25}$ J/cm^2), {$0.56t^{0.25}$ J/cm^2}] {*Table 5a* ANSI Std.}

= 0.56 (10 x 10^{-9})$^{0.25}$ J/cm^2

$MPE_{s.p.}$ = 5.60 x 10^{-3} J/cm^2

Rule 2 (CW/ pulse):

For the wavelength region 315 nm to 400 nm with exposures on the order of 10 to 30,000 seconds the photochemical limit MPE is defined as, "1 J/cm^2" and the **thermal limit does not apply** [*ANSI Std. Z136.1-2000 (Table 5a)*].

T = 30,000 seconds

$$MPE_{rule2} = \frac{MPE}{n} = \frac{MPE}{PRF \cdot T}$$

MPE = 1 J/cm^2 $ANSI\ \ Table\ \ 5a : \left\{ 10\ \ \sec \le T \le 3 \times 10^3\ \ \sec \right\}$

$$MPE_{rule2} = \frac{1 \, {}^{J}\!/\!{}_{cm^2}}{(30)\ \left(30 \times 10^3\right)} = \frac{1}{900 \times 10^3} \, {}^{J}\!/\!{}_{cm^2}$$

$$MPE_{rule2} = 1.11 \times 10^{-6} \, {}^{J}\!/\!{}_{cm^2}$$

Rule 3 (Multiple Pulses):

ANSI Rule 3 **applies only to the thermal limit** [*ANSI Std. Z136.1-2000 (8.2.3.1)*] and is generally the product of the single pulse MPE and a pulse correction factor (C_p), the form of which is given in *ANSI Std. Z136.1-2000 (Table 6)*.

For T = 3 x 10^4 seconds:

$$MPE_{rule3} = C_p MPE_{s.p.-thermal}$$

$$= n^{-0.25} MPE_{s.p.-thermal} = \left(PRF \cdot T\right)^{-0.25} MPE_{s.p.-thermal}$$

$$= \left[\left(30\sec^{-1}\right)\ \left(30 \times 10^3 \sec\right)\right]^{-0.25} \left(5.60 \times 10^{-3}\ {}^{J}\!\!\diagup_{cm^2}\right)$$

$$= \left[900 \times 10^3\right]^{-.025} \left(5.60 \times 10^{-3}\ {}^{J}\!\!\diagup_{cm^2}\right) = \left(32.5 \times 10^{-3}\right)\ \left(5.6 \times 10^{-3}\ {}^{J}\!\!\diagup_{cm^2}\right)$$

$$MPE_{rule3} = 182 \times 10^{-6}\ {}^{J}\!\!\diagup_{cm^2}$$

Summary Table

Table 1

Appropriate UV MPE

(315 nm < λ < 400 nm), 30,000 Seconds, Initial (1st Day) Exposure

ANSI Rule	MPE **(J/cm²)**	Comment
1	5.60×10^{-3}	
2	$\mathbf{1.11 \times 10^{-6}}$	**Appropriate MPE**
3	182×10^{-6}	

ANSI Rule 2 provides the appropriate, "worst case", MPE for a 30,000 second exposure. The "worst case" MPE is always used for the determination of the minimum optical density necessary for the appropriate eyewear.

The actual MPE is used to determine the appropriate NOHD. The actual appropriate MPE is a function of the "actual exposure", which is expected to be much less than 30,000 seconds. The "actual" appropriate MPE as a function of exposure time (1 to 30,000 seconds) is presented in the following plot.

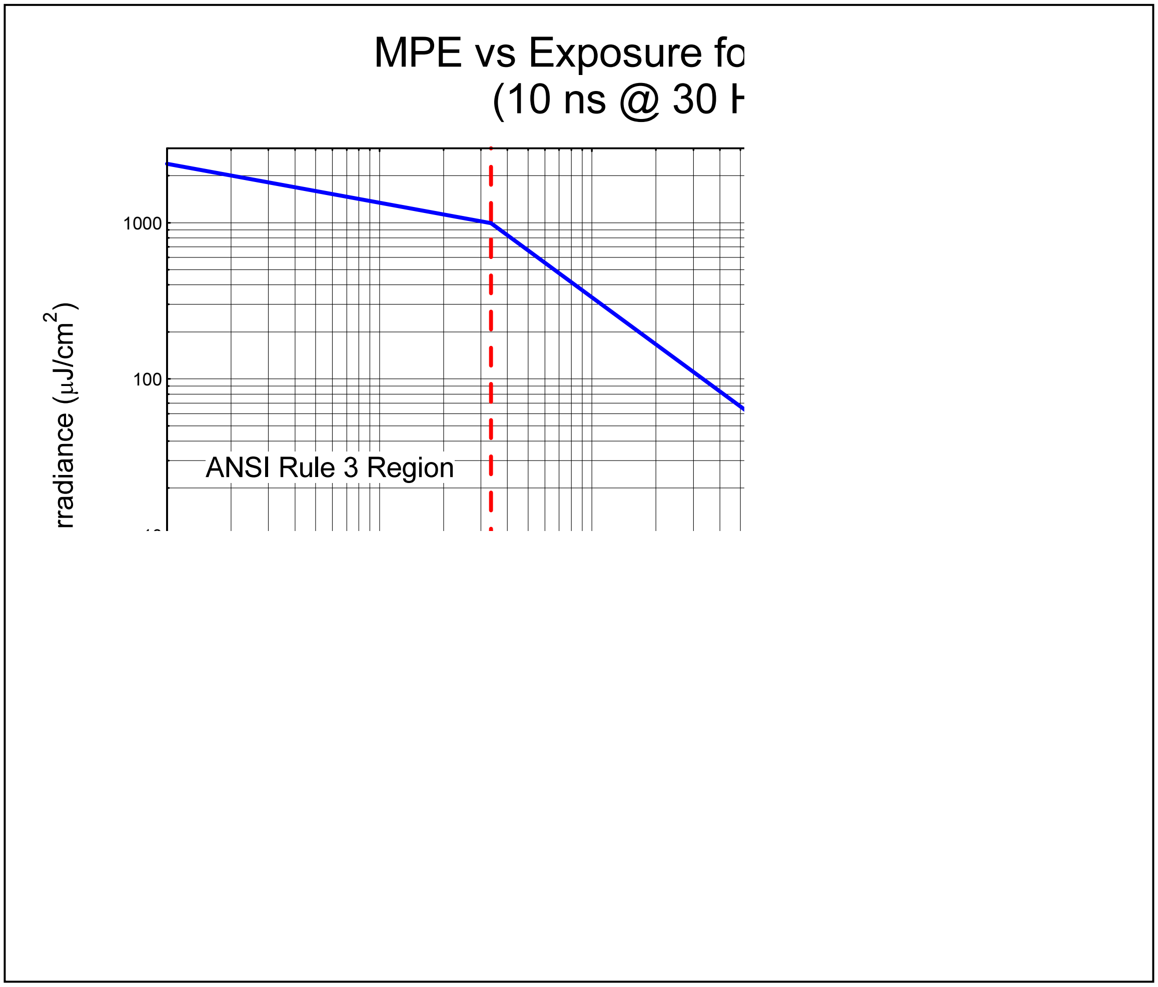

Figure 1

Plot of maximum permissible exposure (MPE) for 355 nm, 10 ns pulses at 30 Hz.

3. ANSI Rule 3 to Rule 2 Crossover

The "rule crossover point" occurs at the exposure duration where the appropriate MPE calculated from ANSI Rule 2 is equaled that calculated from ANSI Rule 3.

$$MPE_{rule3} = MPE_{rule2}$$

$$n_x^{-0.25}\left\{ 0.56t^{0.25} \,{}^{J}\!/_{cm^2} \right\} = \frac{1\,{}^{J}\!/_{cm^2}}{n_x}$$

$$n_x^{3/4} = \frac{1}{0.56t^{0.25}}$$

$$n_x = \left[\frac{1}{0.56t^{0.25}}\right]^{4/3}$$

For t = 10 ns:

$$n_x = \left[\frac{1}{0.56\,\left(10^{-8}\right)^{0.25}}\right]^{4/3}$$

$$n_x = 1{,}005.58 \quad pulses$$

Note: Fractional pulse counts are rounded to the next higher integer.

Crossover time (T_x) can be calculated as follows:

$$n_x = PRF \cdot T_x \Rightarrow T_x = \frac{n_x}{PRF} = \frac{1006}{30\sec^{-1}}$$

$$T_x = 33.53 \ \sec$$

4. <u>MPE For Successive Day Exposure</u>

The MPE for successive day or second day exposure to UV emissions with wavelengths longer than 280 nm requires that the MPE to be de-rated by a factor of 2.5 [*ANSI Std. Z136.1-2000 (8.2.3.1)*].

$$MPE_{2^{nd}\,Day} = \frac{MPE_{315nm-400nm}}{2.5} = \frac{1.11\times10^{-6}\,J/cm^2}{2.5}$$

$$MPE_{2^{nd}\,Day} = 444\times10^{-9}\,J/cm^2$$

B. MPE Determination For: The IR (1064 nm) Rangefinder

Infrared Region (1050 nm ≤ λ < 1400 nm):

The fundamental wavelength of the Nd:YAG pump laser is 1.064 μm (1064 nm). Although most of the IR pulse energy is used in the wavelength conversion to the third harmonic (355 nm) there is always some energy "left over" at the fundamental wavelength. Normally, the residual 1064 nm and the 532 nm light is separated inside the laser head (using dichroic beam splitters) and residual energy is sent to appropriate beam dumps. However, in the AURA system, a small fraction of the residual 1064 nm light is retained in the output and is available to be used as a rangefinder pulse. The IR emission from the AURA system is expected to be about 1.5 millijoule (mJ) but could be as high as 2 mJ.

Full Protection (T = 10 seconds)

The standard (1064 nm) IR laser exposure is, given by the *ANSI Std. Z136.1-2000 (Table 4a)* and section *(8.2.2)* as, 10 seconds. The appropriate MPE for a repetitively pulsed laser is always the smallest value derived by the application of ANSI Rules 1 through 3 to *ANSI Std. Z136.1-2000 (Table 5a)*.

Rule 1 (Single Pulse):

The single pulse MPE form for a 10-nanosecond, 1064 nm laser pulse is given by *ANSI Std. Z136.1-2000 (Table 5a)* as:

$$MPE_{s.p.} = 5.0\ C_c \times 10^{-6}\ \text{J/cm}^2 \qquad \left\{1050\ nm \le \lambda < 1400\ nm\right\}$$

$$\left\{10^{-9}\ \text{sec} \le t < 50 \times 10^{-6}\ \text{sec}\right\}$$

{*ANSI Std. Z136.1-2000 (Table 6)*}

$$Cc = 1.0 \qquad \left\{1050\ nm \le \lambda < 1150\ nm\right\}$$

$$\mathbf{MPE_{s.p.} = 5.0 \times 10^{-6}\ J/cm^2}$$

Rule 2 (CW per pulse):

For a standard 10-second IR (1050 nm to 1400 nm) exposure the appropriate form of the MPE is given by *ANSI Std. Z136.1-2000 (Table 5a)* as:

$$MPE_{10\sec} = C_A \times 10^{-3}\ {}^{w}\!/_{cm^2} \qquad \textit{for}\ 10\sec \le t \le 30\times10^{3}\sec$$

The per-pulse MPE is:

$$MPE_{rule2} = \frac{MPE_{10\sec}\cdot T}{n} = \frac{MPE_{10\sec}\cdot T}{PRF\cdot T} = \frac{MPE_{10\sec}}{PRF}$$

$$MPE_{rule2} = \frac{5\times10^{-3}\ {}^{w}\!/_{cm^2}}{30\sec^{-1}}$$

$$MPE_{rule2} = 167\times10^{-6}\ {}^{J}\!/_{cm^2}$$

Rule 3 (Multiple-Pulse):

T = 10 seconds
n = 300 pulses

$$MPE_{rule3} = n^{-0.25} MPE_{s.p.} = (PRF\cdot T)^{-0.25} MPE_{s.p.}$$

$$= (300)^{-0.25}\left[5\times10^{-6}\ {}^{J}\!/_{cm^{-2}}\right] = (0.24)\left[5\times10^{-6}\ {}^{J}\!/_{cm^2}\right]$$

$$MPE_{rule3} = 1.2\times10^{-6}\ {}^{J}\!/_{cm^2}$$

Summary MPE Table For: The 1064 nm Output:

Table 2

Appropriate IR MPE

(1064 nm, 10 Seconds)

ANSI Rule	MPE (J/cm^2)	Comment
1	5.0×10^{-6}	
2	167×10^{-6}	
3	**1.2×10^{-6}**	**Appropriate MPE**

IV. Allowable Emission/Exposure Limit

The laser hazard class Allowable Emission Limit (AEL) is the largest radiant output a laser may have and still remain in that particular hazard class. If it is assumed that the entire emission enters the "eye" than this can also be considered an Allowable Exposure Limit. The AEL is then the allowable exposure limit for that laser hazard class. The AEL will hereafter refer to the maximum radiant exposure for a Class 1 laser hazard.

Appropriate AEL Determination

The appropriate AEL is the product of the appropriate MPE and the area associated with the limiting aperture in *ANSI Std. Z136.1-2000 (Table 8)*.

$$AEL = (MPE)\ (A_{lim})$$

A. <u>AEL For: 355 nm</u>;

The appropriate AEL for the wavelength-range, 315 nm to 400 nm, is the product of the de-rated MPE, for successive day exposures, and the limiting Area. The appropriate limiting aperture is given as 3.5 mm [*ANSI Std. Z136.1-2000 (Table 8)*].

$$AEL_{355nm} = (MPE_{2nd\ day})\,(A_{lim})$$

$$= \left(444 \times 10^{-9}\, J\!\!\diagup_{cm^2}\right)\left[\frac{\pi(0.35cm)^2}{4}\right]$$

$$\mathbf{AEL_{355nm} = 42.7 \times 10^{-9}\ J}$$

B. <u>AEL For: 1064 nm</u>

The AEL for a 1064 nm pulsed laser source is the product of the appropriate MPE and the area of the 7-mm limiting aperture indicated in *Table 8* of the ANSI standard.

$$AEL_{1064nm} = (MPE)\,(A_{lim})$$

$$= \left(1.2 \times 10^{-6}\, J\!\!\diagup_{cm^2}\right)\left[\frac{\pi(0.7cm)^2}{4}\right]$$

$$\mathbf{AEL_{1064nm} = 462 \times 10^{-9}\ J}$$

V. Ground Operation

A. Overview

Personnel involve in airborne AURA - BSLT laser ground operations, such as the optical system alignment and calibration, as well as some laser-interaction tests have the potential for exposure to hazardous emissions above the MPE.

Personnel involved in airborne AURA ground operations are required to wear laser safety eyewear. The laser safety eyewear must, at minimum, have an optical density (OD), which reduces the transmitted radiance to the AEL or less.

B. Minimum Optical Density Calculations

(1) **For 355 nm: 60 mJ (maximum output) @ 30 Hz:**

Use AEL for successive day exposure.

$$OD_{\min} = \log_{10}\left(\frac{Q_0}{AEL_{2^{nd}\,day}}\right)$$

$$= \log_{10}\left(\frac{60\times10^{-3}J}{42.7\times10^{-9}J}\right)$$

$$\mathbf{OD_{min} = 6.15}$$

(2) **For 1064 nm: 2 mJ (maximum output) @ 30 Hz:**

$$OD_{\min} = \log_{10}\left(\frac{Q_o}{AEL_{1064nm}}\right)$$

$$= \log_{10}\left(\frac{2.0\times10^{-3}J}{462\times10^{-9}J}\right)$$

$$\mathbf{OD = 3.64}$$

Personnel who may be within the AURA (BSLT) NHZ for ground operation are expected to be exposed to the ocular hazard tabulated below and are required to wear laser safety eyewear with minimum OD(s) in the wavelength ranges indicated. It is assumed that authorized laser workers shall be subjected to successive day exposures.

Table 3

Minimum Optical Density for Laser Safety Eyewear

(Ground Operation)

Wavelength (nm)	**Radiance (mJ)**	**Exposure** (Seconds)	**OD_{min}**
355	60	30,000	6.15
1064	2	10	3.64

VI. Airborne Operation

A. Overview

The propagation range (distance the laser beam travels to the termination point) is greater than the operational altitude (vertical distance AGL) of the airborne AURA because the beam does not necessarily propagated directly down (nadir) from the Proteus platform, but may be directed at an angle by as much as 27 degrees off of relative vertical. For simplicity and an added safety factor it is assumed that the propagation distance is the altitude of the Proteus platform.

The altitude of the Proteus platform will be maintain such that the AURA laser presents a Class 1 (eye safe) laser hazard to personnel in the “target” area. The Proteus’ altitude above ground level, during laser operation, will always be equal to or greater than the Nominal Ocular Hazard Distance.

B. Nominal Ocular Hazard Distances

The Nominal Ocular Hazard Distance, NOHD, (*ANSI Std. Z136.1-2000*) is the range (R_{NOHD}) to the Safe Eye Exposure Distance (SEED). This can also be considered the distance from the laser to the boundary of the Nominal Hazard Zone (NHZ) if the ocular threat is greater than the skin damage threat. The NOHD can be calculated using the formula presented in the appendix of *ANSI Std. Z136.1-2000*.

This is “worst case”, where there is assumed <u>no</u> attenuation due to atmospheric effects.

$$R_{NOHD} = \frac{1}{\theta}\sqrt{\frac{4Q_o}{\pi \ MPE} - d^2}$$

<u>Where</u>:

R_{NOHD} Nominal Ocular Hazard Distance, SEED = NHZ, in centimeters.
θ Beam divergence, in radians.
Q_o Radiance (Average Pulse Energy), in Joules.
MPE Applicable per pulse Maximum Permissible Exposure-intrabeam viewing, in J/cm^2.
d Beam diameter at the exit of the laser, in centimeters.

For Repetitively Pulsed Lasers:

$$R_{NOHD} = \frac{1}{\theta}\sqrt{\frac{1.27Q_o}{MPE_{/\,pulse}} - d^2}$$

Where:

R_{NOHD}	Nominal Ocular Hazard Distance, SEED = NHZ, in centimeters.
$MPE_{/pulse}$	Applicable Per Pulse Maximum Permissible Exposure, in J/cm^2.
Q_o	Radiant Energy (pulse energy) Output, in Joules.
d	Beam diameter at the exit of the laser, in centimeters.

C. Maximum "Lock-On" Time as a Function of Operational Altitude

The maximum dwell time on target (Lock-On Time) is a function of the effective ground speed, the maximum angular range (forward to aft), and the operational altitude.

$$T_{Lock-On} = \frac{2(h)\tan(\alpha_{\max})}{v_g}$$

Where:

$T_{Lock\text{-}On}$	Maximum Lock-On Time
h	Operational Altitude
α_{max}	Maximum Point Angle
v_g	Ground Speed

Table 4

Proteus Flight Characteristics

Typical Ground Speed (Proteus)	90 Kn (46.3 m/sec)
Operational Altitude	1 km to 5 km
Angular Range (forward to aft)	± 27º

Table 5

Lock-On Times

(As A Function Of The Operational Altitude Single Pass and for 32 Passes)

Operational Altitude (km)	Maximum Lock-On Time Single Pass (Seconds)	Maximum Lock-On Time 32 Passes (Seconds)
1.0	22	704
1.5	33	1056
2.0	44	1408
2.5	55	1760
3.0	66	2112
3.5	77	2464
4.0	88	2816
4.5	99	3168
5.0	110	3520

D. NOHD (As A Function Of Exposure)

The UV NOHD can be plotted as function of the exposure duration for the airborne AURA laser radiant output. Atmospheric transmission* attenuation was not considered which yields results with a conservative safety bias (safety factor).

The **safety factor**† is the inverse square root of the atmospheric transmission.

***Atmospheric transmission** (τ) in clear air at wavelength (355 nm) is: 0.769 @ 1 km, 0.638 @ 2 km, 0.562 @ 3 km, 0.52 @ 4 km and 0.49 @ 5 km.

Atmospheric transmission correction compresses the NHZ at the square root of the atmospheric transmission factor:

$$NOHD_{atmospheric} = \left(\sqrt{\tau}\right) \cdot \left[NOHD\right]$$

†Safety Factor:

$$Safety\_factor = \frac{NOHD}{NOHD_{atmospheric}} = \frac{1}{\sqrt{\tau}}$$

Safety factor associated with atmospheric transmission ranges from 1.14 at 1 km to 1.43 at 5 km.

Typical Output (over target area):

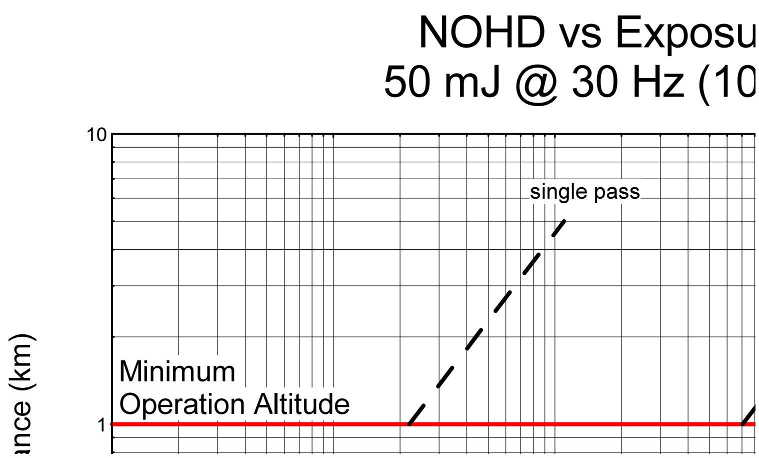

Figure 2

The plot of the Nominal Ocular Hazard Distance (NOHD) as a function of exposure for typical laser output (over the target area) shows that unauthorized as well as authorized personnel are outside the hazard zone.

Flight conditions for a single pass to 32 passes at typical laser output place personnel, unauthorized as well as authorized, on the ground well outside the hazard zone.

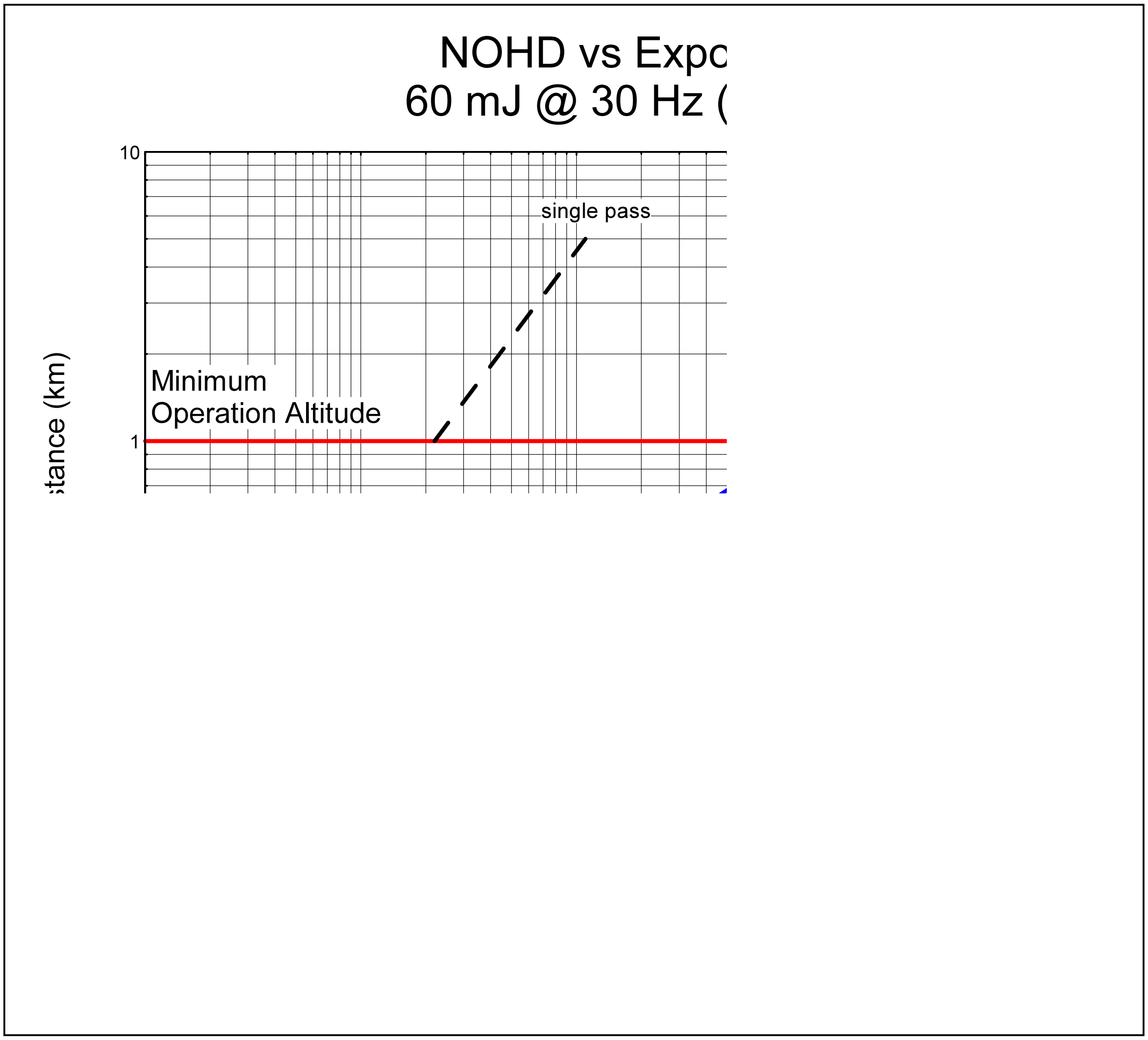

Figure 3

A plot of the Nominal Ocular Hazard Distance (NOHD) as a function of exposure for maximum laser output (over the target area) shows that unauthorized as well as authorized personnel are outside the hazard zone.

Flight conditions for a single pass to 32 passes at maximum laser output place personnel, unauthorized as well as authorized, on the ground outside the hazard zone.

Worst Case: for both UV and IR Maximum Outputs.

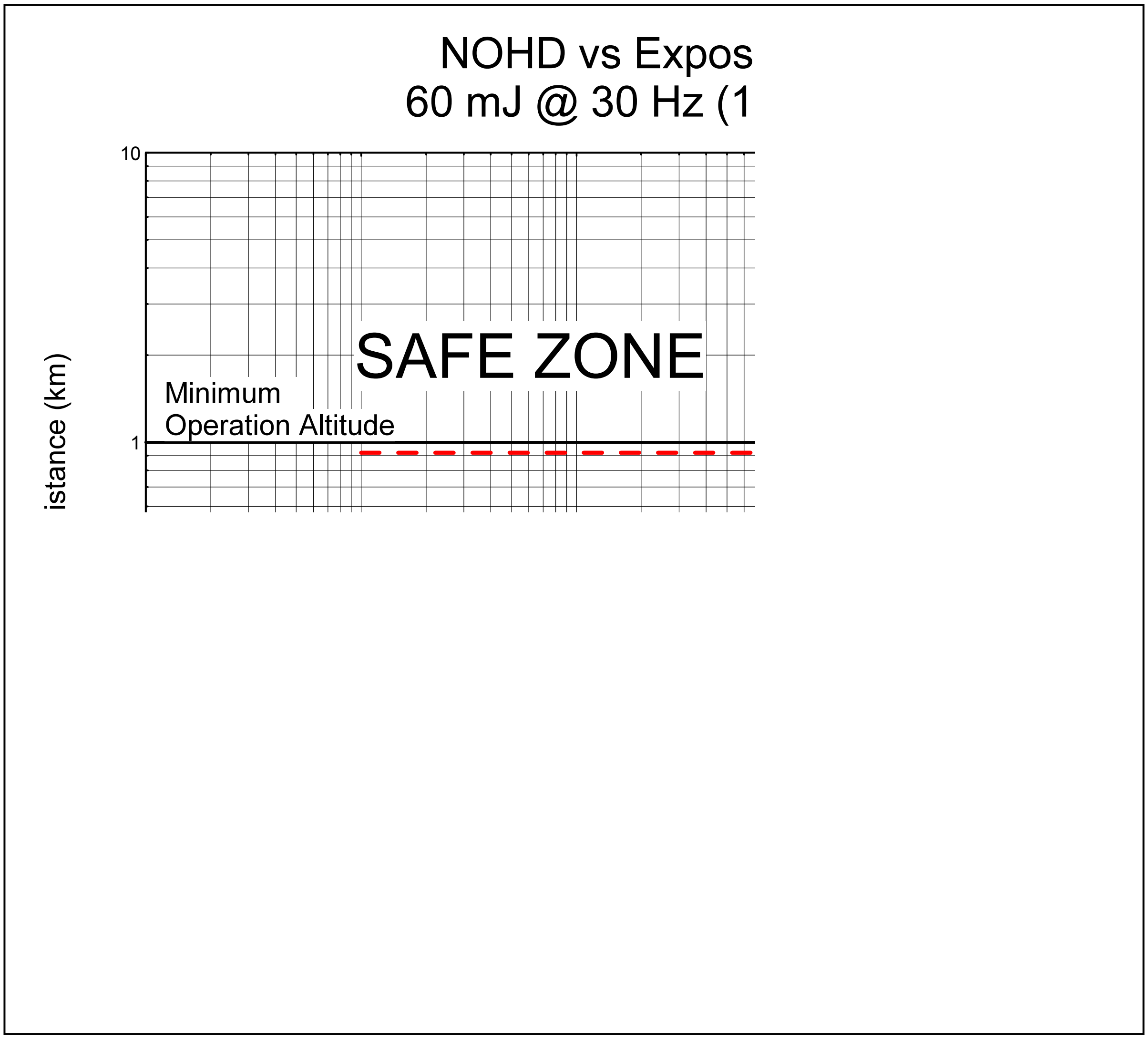

Figure 4

A plot of the NOHD as a function of exposure for worst case for maximum UV and IR output (over the target area) shows that flight conditions for an 8-hour flight place all effected personnel outside the hazard zone.

Flight conditions for an eight-hour flight (32 passes) at maximum laser output (UV and IR) place personnel on the ground outside the laser hazard zone.

For accumulative exposures up to ~1,000 seconds the ocular hazard posed by the IR laser output (2 mJ per pulse) dominates and determines the NOHD of the airborne AURA laser system. For accumulative exposures greater than 1,000 seconds the hazard posed by the UV laser output dominates and determines the NOHD for the airborne AURA laser system. Distances greater than the NOHD are eye/skin safe zones. Ground personnel are outside the hazard zone even at maximum output for maximum duration.

E. Exclusion Zone About The Proteus Aircraft.

The radiant output wavelengths of the airborne AURA are outside the visible spectrum as defined by *ANSI Std. Z136.1-2000**, *ANSI Std. Z136.6-2000*†, and *FAA7400.2D Chapter 34** and do not pose a visual interference (distraction, disruption, or disorientation) concern for aircrews in navigable air space. Startle, dazzle, flashblindness and glare concerns apply only to visible light and do not apply to invisible laser beams. The critical zone exposure distances (CZED) and the sensitive zone exposure distance (SZED) do not apply.

The NOHD for invisible as well as visible laser light applies in Normal Flight Zone (NFZ).

The Proteus minimum "ground speed" is 90 knots (46.3 m/sec). At a PRF of 30 hertz the spatial separation between pulses is more than 1.5 meters. The normal human pupil size is on the order of 7 mm in daylight (the limiting apertures listed in *ANSI Table 8* are normalization factors and not physical sizes). Given relative motion between the laser (Proteus) and an unknown observer (another aircraft) an accidental exposure would entail no more than at most one laser pulse. Although the probability of an exposure is extremely unlikely an exclusion zone, about the Proteus, of at least the single pulse NOHD is required.

The single pulse NOHD or SEED for both IR and UV emissions is given for typical and maximum outputs.

Table 6

Single Pulse SEED
(No transmission factor adjustment)

Wavelength (nm)	**Pulse Energy** (mJ)	**SEED** (meters)
355	**50**	**64.4**
355	**60**	**71.1**
1064	**1.5**	**390**
1064	**2.0**	**451**

The greatest SEED is, for the IR at maximum output (2 mJ), 451 meters (~1480 feet).

The airborne AURA laser single pulse hazard zone (airspace exclusion zone about the aircraft) extends from the aircraft to 1,480 feet below the Proteus and out to 672 feet forward and to 672 feet aft, and out to 308 feet to either side of the aircraft.

*Visible: 400 nm $\leq \lambda \leq$ 700 nm,
†Visible: 380 nm $\leq \lambda \leq$ 780 nm

Airspace Exclusion Zone Below and About the Proteus

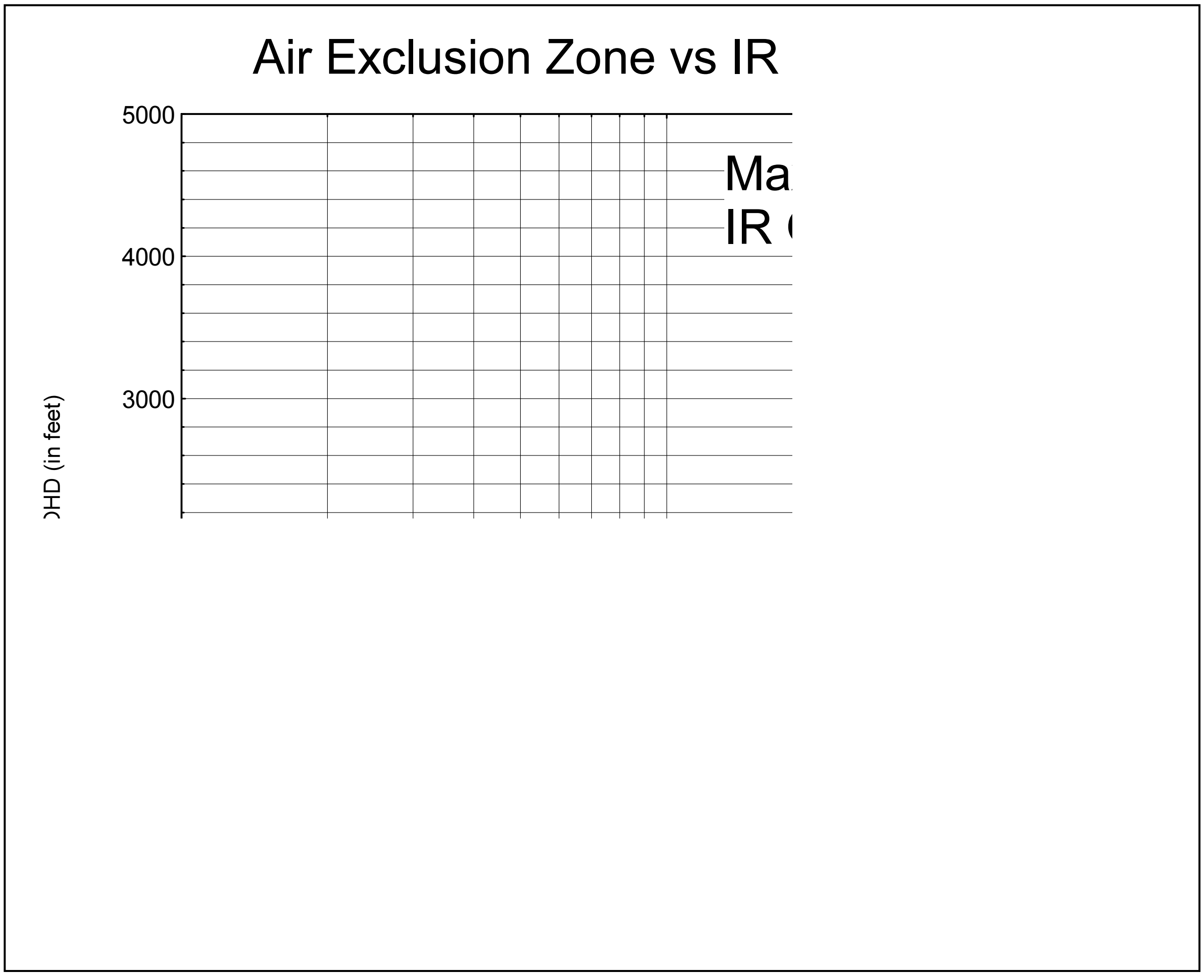

Figure 5

Plot of the Air Exclusion Zone versus the rangefinder IR output pulse energy.

Aircrew exposure, outside the NOHD (exclusion zone), are in the eye safe zone.

Startle, dazzle, flashblindness and glare visual interference concerns do not apply for invisible laser light (UV & IR).

F. Eye Safe Dwell Time For Ground Personnel versus Operational Altitudes

Plotting time versus range gives Dwell Time versus Altitude (with atmospheric transmission factors not considered).

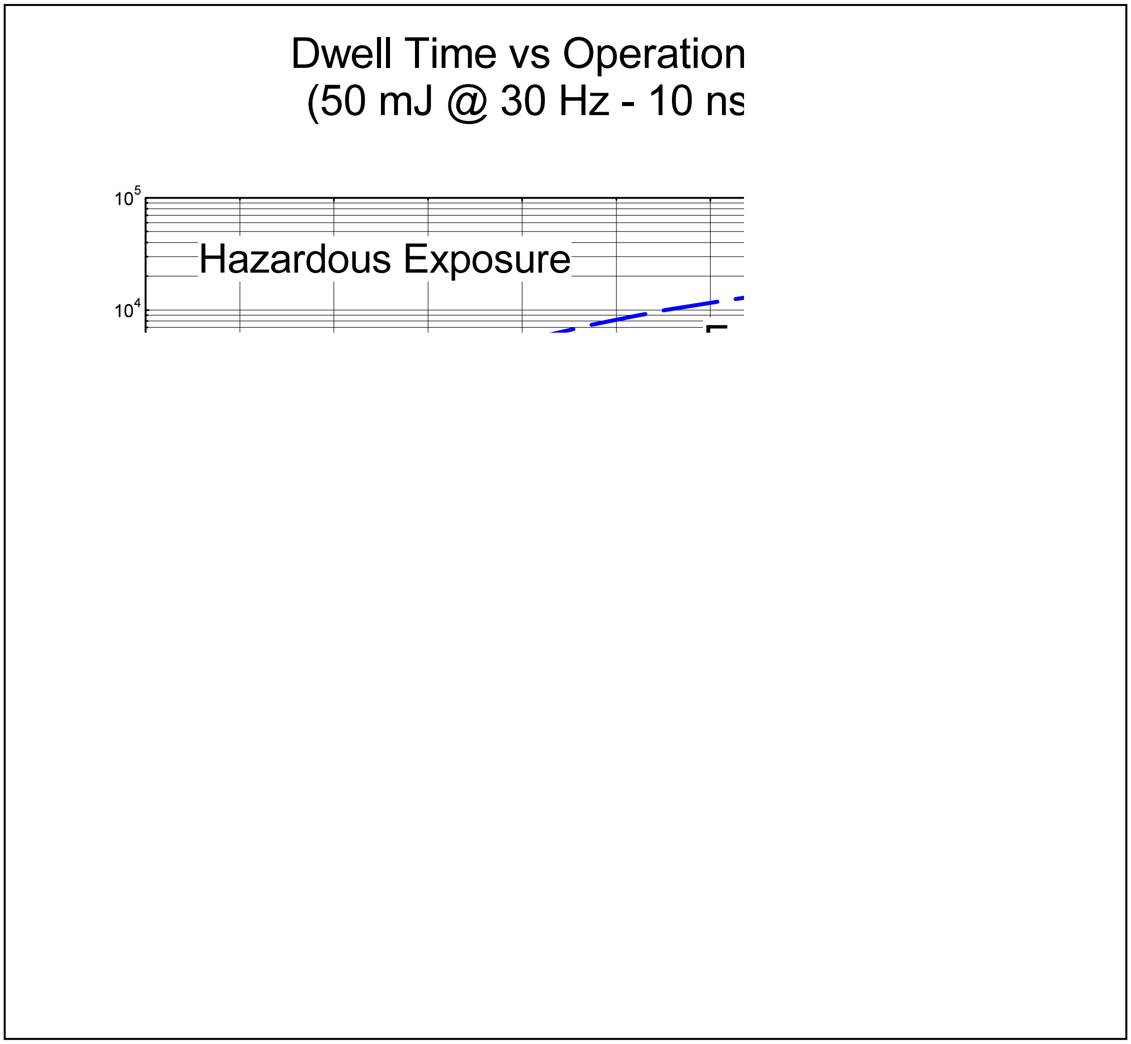

Figure 6

A plot of eye safe dwell times for ground personnel versus Proteus operational altitudes for typical laser outputs indicates the Proteus flight conditions place effected personnel outside the hazard zone.

Flight conditions for a single pass to 32 passes at typical laser output place personnel on the ground outside the hazard zone and conditions are eye safe.

Maximum Output:

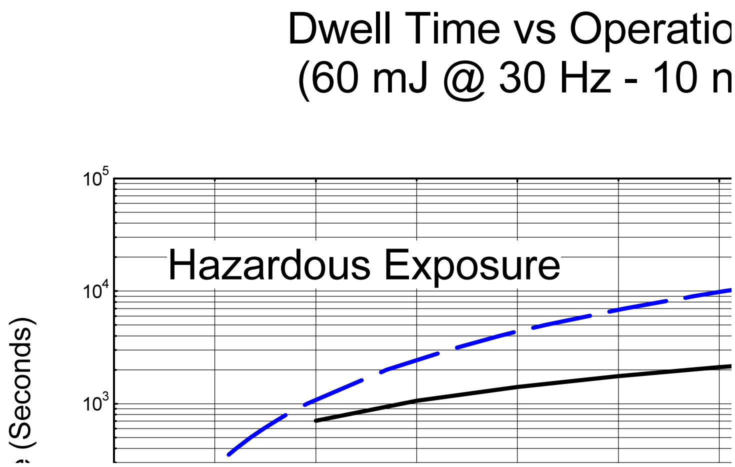

Figure 7

A plot of eye safe dwell times for ground personnel versus Proteus operational altitudes for maximum laser outputs indicates the Proteus flight conditions place effected personnel outside the hazard zone.

Flight conditions for a single pass to 32 passes at maximum laser output place personnel on the ground outside the hazard zone and conditions are eye safe.

VII. Conclusions

Even under the worst-case conditions the AURA lidar system is eye safe for ground personnel in the target area.

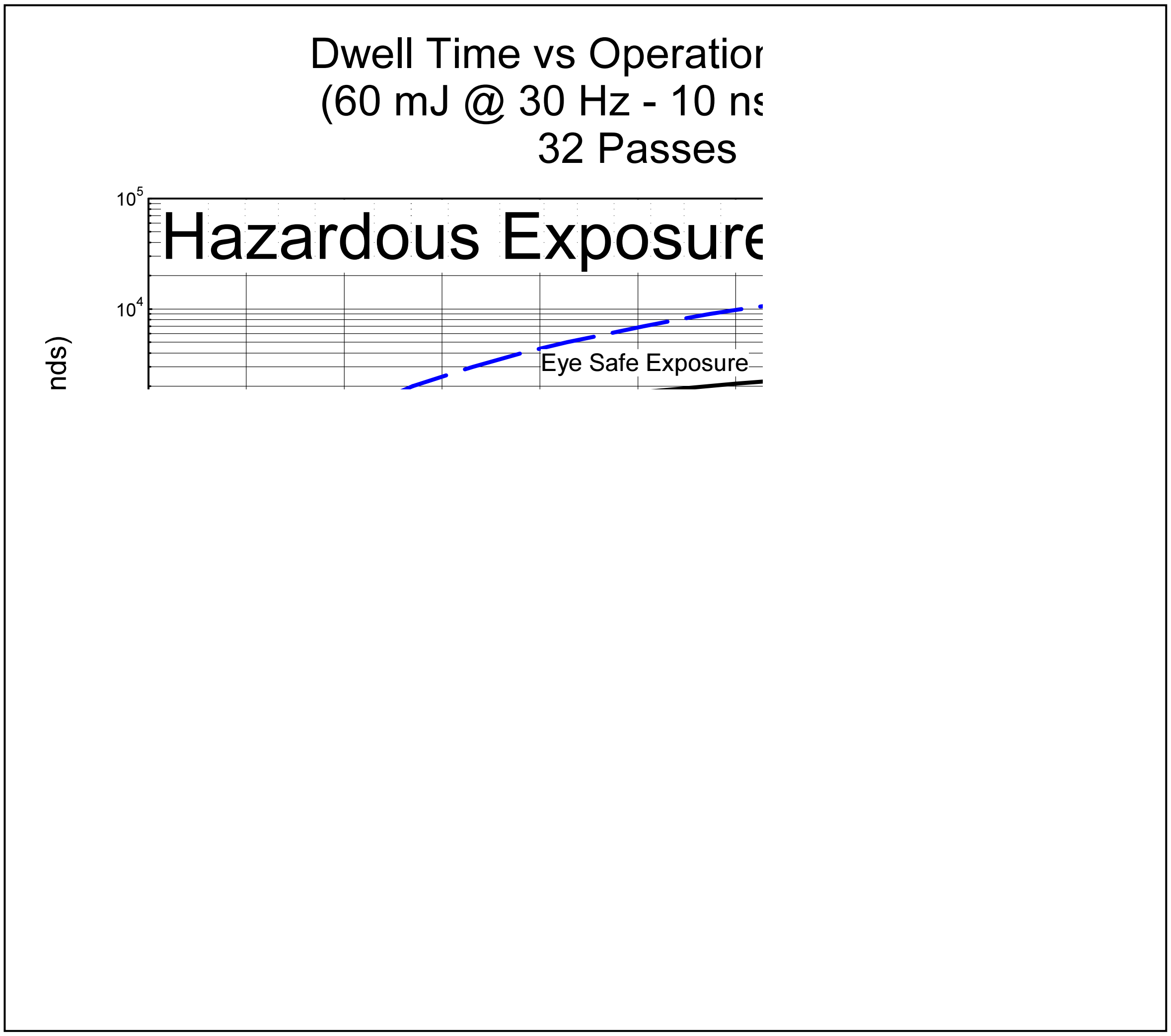

Figure 8

A plot of the eye safe dwell times for ground personnel versus Proteus operational altitudes for maximum laser outputs (UV & IR) indicate the Proteus flight conditions for an eight hour flight place effected ground personnel outside the ocular hazard zone. The ground area is eye safe even under worst-case conditions.

IR & UV Hazard Dominance

For accumulated exposures up to about 1,000 seconds the ocular hazard distance (921 meters) and the NHZ is dominated by the IR laser hazard. For accumulated exposures greater than 1,000 seconds the ocular hazard distance and the NHZ is dominated by the

UV laser hazard. The expected exposure determined by the flight characteristics of the Proteus is **eye safe** even under "worse case" conditions (maximum laser output in the UV and IR and maximum dwell time on target over an 8 hour flight).

VIII. References

ANSI Std. Z136.1-2000: for Safe Use of Lasers, Published by the Laser Institute of America.

ANSI Std. Z136.6-2000: for Safe Use of Lasers Outdoors, Published by the Laser Institute of America.

FAA 7400.2D Chapter 34, Outdoor Laser/High Intensity Light Demonstrations

IX. Abbreviations

AEL	Allowable Emission (Exposure) Limit
AF	Air Force
AFRL	Air Force Research Laboratory
A_{lim}	Area of limiting aperture
ANSI	American National Standard Institute.
C_p	Multiple pulse correction factor.
CW	Continuous wave.
CZED	Critical Zone Exposure Distance
d_{aid}	Entrance diameter of optical aid.
d_{exit}	Exit diameter of the telescope.
d_{lim}	Diameter of limiting aperture.
d_o	Output beam diameter.
E	Irradiance, in J/cm^2.
E_o	Output Irradiance, in J/cm^2.
EOHD	Extended Ocular Hazard Distance.
Hp	Irradiance of the beam over the limiting aperture.
Hz	Hertz, cycle per second, sec^{-1}.
J	Joules, unit of energy.
Min[a,b]	Minimum of value of a and b.
mJ	Millijoule, 10^{-3} Joules.
MPE	Maximum Permissible Exposure.
MPE	
MPE_{cw}	Continuous Wave Maximum Permissible Exposure.
$MPE_{/pulse}$	Per Pulse Maximum Permissible Exposure.
$MPE_{m.p.}$	Multiple Pulse Maximum Permissible Exposure.
$MPE_{s.p}$	Single Pulse Maximum Permissible Exposure.
mw	Milliwatts, 10^{-3} watts
NFZ	Normal Flight Zone
nm	Nanometer, 10^{-9} meters.
NOHD	Nominal Ocular Hazard Distance.
ns	Nanosecond, 10^{-9} seconds.
NHZ	Nominal Hazard Zone.
OD	Optical Density of the laser safety eye ware.

OD_{min}	Minimum Optical Density required of laser safety eyewear.
PRF	Pulse Repetition Frequency.
Q	Radiant Energy, in Joules.
Q_o	Output Radiant Energy, in Joules.
SZED	Sensitive Zone Exposure Distance
t	Exposure duration, pulse duration
t_b	Boundary time between photochemical and thermal limits
t_d	Dwell time.
T	Exposure duration, in seconds.
T_x	Cross-over time between ANSI Rule 3 and ANSI Rule 2
α	Viewing angle.
θ	Beam divergence.
Φ	Radiant Power.
λ	Wavelength
μm	Micrometer, 10^{-6} meters.
τ	Transmission factor.
τ_{aid}	Transmission factor of optical aid
τ_{atm}	Atmospheric transmission factor.

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